Published online August 9, 2005

Soil Properties Affecting Wheat Yields following Drilling-Fluid Application

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ABSTRACT

Oil and gas drilling operations use drilling fluids (mud) to lubricate the drill bit and stem, transport formation cuttings to the surface, and seal off porous geologic formations. Following completion of the well, waste drilling fluid is often applied to cropland. We studied potential changes in soil compaction as indicated by cone penetration resistance, pH, electrical conductivity (EC_e), sodium adsorption ratio (SAR), extractable soil and total straw and grain trace metal and nutrient concentrations, and winter wheat (*Triticum aestivum* L. 'TAM 107') grain yield following water-based, bentonitic drilling-fluid application (0–94 Mg ha^{-1}) to field test plots. Three methods of application (normal, splash-plate, and spreader-bar) were used to study compaction effects. We measured increasing SAR, EC_e, and pH with drilling-fluid rates, but not to levels detrimental to crop production. Field measurements revealed significantly higher compaction within areas affected by truck travel, but also not enough to affect crop yield. In three of four site years, neither drilling-fluid rate nor application method affected grain yield. Extractions representing plant availability and plant analyses results indicated that drilling fluid did not significantly increase most trace elements or nutrient concentrations. These results support land application of water-based bentonitic drilling fluids as an acceptable practice on well-drained soils using controlled rates.

The oil and gas drilling industry uses drilling fluid (often referred to as drilling mud or muds) to lubricate and cool the drilling apparatus, transport formation cuttings to the surface, and seal off porous geologic formations. Following completion of a well, spent drilling fluids and formation cuttings are allowed to settle in a reserve pit before disposal. Waste drilling fluids are often land-applied following completion of an oil or gas well in Colorado and other areas of the Western United States. This material usually contains production water, bentonitic clays, formation cuttings, barite, Na compounds, and synthetic organic polymers. During the early 1990s, explosive growth in natural gas drilling created over 800 000 m^3 of mixed water, mud, and formation cuttings in one Colorado county (Weld) in two years (L. Avis, Colorado Oil and Gas Conservation Commission, personal communication, 1995) with much of this material applied to agricultural land. More recently, high natural gas prices coupled with political mandates to explore domestic energy sources have increased drilling activity in the Western United States with an accompanied increase in waste drilling-fluid production. For example, Colorado drilling permits for oil and gas wells increased by over 100% from 2000 to 2003 (Anonymous, 2004).

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Published in J. Environ. Qual. 34:1687–1696 (2005).
Technical Reports: Waste Management
doi:10.2134/jeq2004.0384

Few studies have addressed the impact of drilling-fluid land application on plant growth and soil properties. Previous research indicates that the drilling-fluid impact on plant growth is largely negative due to high plant available trace metals and soluble salts (Nelson et al., 1984; Miller et al., 1980; McFarland et al., 1992a, 1992b, 1994; Younken and Johnson, 1980). However, some researchers (Nelson and Mikesell, 1982) also found positive or no impact from drilling fluids applied at lower rates or drilling fluids produced with more benign materials. Differences between studies have primarily resulted from the wide range of drilling-fluid components and rates used by various investigators. The fate of trace metals in soil following drilling-fluid application has also been investigated. Some workers (Deeley and Canter, 1986) conducted fractionation studies that suggested trace metals would not be significantly released while others (Bates, 1988) found increases in plant available forms of trace metals and movement in a column study.

Impacts of application on farm land in Colorado are primarily anecdotal, with some farmers claiming improved moisture retention on sandy soils (L. Avis, Colorado Oil and Gas Conservation Commission, personal communication, 1995). The Colorado Oil and Gas Conservation Commission (Anonymous, 2001) lists land application of water-based bentonitic fluids disposal as an acceptable method of disposal with limits on the depth of the drilling fluid. The waste shall be applied to prevent ponding or erosion and must be incorporated as soon as practicable. The regulations also specify limits following application for concentrations of metals and total petroleum hydrocarbons in soil, and limit soil EC_e to less than 4.0 dS m^{-1} or two times background, SAR to less than 12, and pH to 6 to 9.

The drilling-fluid hauling contractors in our study area (Weld County, CO) usually land apply waste drilling fluid with water trucks. These vehicles can approach a gross vehicle weight of 25 Mg when fully loaded. Trucks apply the drilling fluid by opening rear-facing valves and driving across fields until empty. While applying drilling fluid, the maximum swath width is about 1.5 to 2.5 m. Drilling-fluid application rates vary greatly due to uneven truck speed, irregular drilling-fluid solids content, changing hydrostatic pressure in trucks, and application overlap. Generally, contractors attempt to utilize most of a field's area and apply drilling fluid in closely

Abbreviations: AB-DTPA, ammonium bicarbonate-diethylenetriaminepentaacetic acid; CSUCTS, Colorado State University Crops Testing Service; EC_e, electrical conductivity saturated-soil paste extract; ICP–AES, inductively coupled plasma–atomic emission spectrophotoscopy; SAR, sodium adsorption ratio.

spaced patterns. We evaluated the combined effects of water-based bentonitic drilling-fluid application and truck travel on crop yield, plant metal uptake, and soil chemical properties using three application methods. A dryland winter wheat (*Triticum aestivum* L. 'TAM 107') cropping system was evaluated during the 1994–1995 and 1995–1996 cropping years in Weld County, CO.

Given the scarcity of research on drilling-fluid impacts following application to cropland, the objectives of this study were to (i) investigate the combined effects of increasing industry-based drilling-fluid rates and potential soil compaction from truck travel on dryland winter wheat yield; (ii) evaluate the current industry method (normal) for application versus spreader-bar and splash-plate methods for their effectiveness in reducing tire impacted soil area and thus crop yield; (iii) determine if increasing drilling-fluid rates change the levels of wheat grain and straw trace metal and nutrient concentrations; and (iv) examine the effect of increasing drilling-fluid rates on soil extractable trace metals and pH, EC_e, and SAR.

MATERIALS AND METHODS

This study was conducted in a dryland wheat–fallow cropping system in Weld County, CO. We used a total of four site years during the 1994–1995 and 1995–1996 cropping years. These sites will be referred to as A1, B1 and A2, B2 for the 1994–1995 and 1995–1996 cropping years, respectively. Sites A1 and A2 are adjacent fields that are located approximately 10.5 km west of Greeley, CO. These sites are dominated by the Colby soil series (fine-silty, mixed, superactive, calcareous, mesic Aridic Ustorthent) (Soil Survey Staff, 1980). Sites B1 and B2 are also adjacent fields and are located approximately 5.6 km northeast of Keenesburg, CO. Sites B1 and B2 contain the Osgood (loamy, mixed, mesic Arenic Ustollic Haplargids) and Olney (fine-loamy, mixed, superactive, mesic Ustic Haplargids) soil series, respectively.

Before drilling-fluid application, we sampled all four site years for baseline analysis. Soil samples taken before drilling-fluid application were analyzed for pH, electrical conductivity (EC_e), and sodium adsorption ratio (SAR) using saturated pastes (Rhoades, 1982). The samples were also analyzed for percent sand, silt, and clay using the hydrometer method and sand-sized fractions using dry sieving (Day, 1965). Selected baseline soil results are presented in Table 1.

A drilling-fluid hauling contractor applied drilling fluid to study plots with dual axial 12 700-L water trucks used in typical oil-field applications. As practiced by industry, we applied drilling fluid through a 30-cm, round gate on the rear of the water truck. This method is referred to as the normal application method. Two other application methods were designed to distribute the drilling fluid over a wider area and to distribute it more uniformly. The first new method was a 4.6-m-long spreader-bar. The spreader-bar was designed to attach to a 10-cm valve on the rear of the water trucks with a quick coupler (spreader-bar method). The bar consists of a 15-cm-diameter pipe with flood-type nozzles welded at 8-cm centers. The third method was a 25-cm-wide, triangular-shaped, splash-plate designed for spreading water for dust control (splash-plate method). This splash-plate also attached to the 10-cm valve with a quick coupler.

Before applying drilling fluid to study plots, the trucks and application methods were carefully calibrated. Calibration of drilling-fluid application methods began by developing a statistical regression line to predict percent solids from a wide range of drilling-fluid wet weights. We collected 32 samples of drilling fluid from eight active drilling sites in Weld County. Samples were weighed on a Baroid (Houston, TX) drilling-fluid balance in the field and oven-dried for 24 h at 105°C to determine percent solids. Linear regression was used to develop the specific gravity/percent solids equation [percent solids = $-88 + 11.4$(balance reading), $R^2 = 0.98$]. This calibration allowed us to calculate application rates on a dry-weight basis in the field.

To calibrate the spreader-bar and splash-plate application methods, we buried 2.5-L plastic paint-mixing buckets with the upper edge 5 cm above ground level at every 6 m of plot length and 1 m across the calibration plots. The buckets covered a known surface area, and we measured the collected drilling-fluid volume with a 1000-mL graduated cylinder following an application pass. The water-truck speed was varied for each rate. By measuring the specific gravity with the drilling-fluid balance, we could determine the percent solids with the regression equation. Thus, we calculated the dry Mg ha^{-1} for each test run in the field. Runs were repeated until ground speed predicted an acceptable, uniform rate. Therefore, we controlled rates for the splash-plate and spreader-bar methods by varying truck speed.

Catching drilling fluid with buckets proved unreliable with the normal method due to nonuniform drilling-fluid distribution. Therefore, we controlled the normal method rates by adjusting hydrostatic pressure (drilling-fluid level in truck) while driving at a constant speed. Before field calibration, the contractor calibrated their truck tank by measuring the height of fluid versus the volume held in the truck with a flow meter. We used truck gauging to verify volume of drilling fluid released during each application run. During calibration we measured greater normal method application rates than the spreader-bar method and splash-plate method application rates. Based on communication with drilling-fluid hauling contractors and field measurements, the normal method represents drilling-fluid rates, truck speeds, and application patterns practiced by contractors (not spill conditions or careless applications). The lower rates obtained using the spreader-bar and

Table 1. Selected soil characteristics at all site years (0–15 cm).

	Year 1		Year 2	
Characteristic†	Site A	Site B	Site A	Site B
pH	7.0	5.8	7.9	6.9
EC_e, dS cm^{-1}	0.26	0.63	0.70	0.46
SAR	ND‡	ND	0.90	0.46
Sand, %	31	75	37	54
Silt, %	41	20	36	30
Clay, %	28	5	27	16
USDA texture	clay loam	sandy loam/loamy sand	loam/clay loam	sandy loam

† EC, electrical conductivity; SAR, sodium adsorption ratio.
‡ Not determined.

Table 2. Drilling-fluid application rates and characteristics from all site years.

Application method and level	Rate† Site and application date A1: 9–10 May 1994	B1: 16–17 June 1994	A2: 28 July 1995	B2: 4 Aug. 1995
	Mg ha^{-1}			
Normal, low	33	54	11	10
Normal, medium	50	72	22	16
Normal, high	70	94	40	30
Splash-plate, low	17	17	8.0	4.5
Splash-plate, medium	35	30	11	7.0
Splash-plate, high	56	54	18	9.0
Spreader-bar, low	21	17	7.0	2.2
Spreader-bar, medium	35	28	11	2.7
Spreader-bar, high	56	43	18	4.5
Specific gravity, g cm^{-3}	1.13–1.29	1.23	1.15–1.24	1.03–1.10
Percent solids, %	18–35	29	22–30	7.2

† Rates expressed on a dry-weight basis.

splash-plate methods were experimental rates. The drilling-fluid application widths were approximately 2, 4.5, and 5 m for the normal, splash-plate, and spreader-bar application methods, respectively. Thus, the normal application method required two passes to apply drilling fluid to the same area as the other two methods. The width of soil impacted by tire tracks in one pass was approximately 1 m.

All site years received a single drilling fluid application during the fallow portion of the rotation in the spring or summer before planting. Variation in drilling-fluid rates between site years resulted from inconsistent drilling-fluid weights available and unexpected changes in drivers and trucks made available on the application dates (Table 2). Additionally, miscommunication between the contractor and the drilling company required us to use drilling fluid from two separate drilling sites (pits) while applying at Site A1. We sampled each truckload at all sites, and oven-dried the drilling fluid at 105°C for 24 h to confirm percent solids. Specific gravity was determined in the field using a Baroid drilling-fluid balance. Following application to each plot, we verified rates as described above.

During application in both site years, we sampled drilling fluid from each truckload. Total HNO_3–$HClO_4$–HF (Lim and Jackson, 1982) and AB-DTPA (Soltanpour, 1985) extractable P, K, Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb, Mo, Al, Mn, V, Si, Ca, and Mg were determined using ICP–AES, As and Se by hydride generation with ICP–AES (Soltanpour et al., 1982), and Hg by cool vapor with atomic absorption (USEPA, 1983). The drilling fluid was also analyzed for total Kjeldahl nitrogen, 2 *M* KCl extractable NH_4–N and NO_3–N, organic matter (Nelson and Sommers, 1996), particle size distribution, cation exchange capacity (Thomas, 1982), percent solids, pH, EC_e, and water soluble Ca, Mg, and Na to calculate a SAR (Rhoades, 1982).

Table 3 presents selected AB-DTPA extractable and total elements contained in the drilling fluid used for both site years. Most of the elements fall into the common range for soils provided by Lindsay (1979) and Kabata-Pendias and Pendias (1989). Exceptions are drilling-fluid Mg, Na, Cd, and Mo, which were found in higher concentrations than typical soils. The elements Na, Cd, and Mo have potential for detrimental effects on soils and plants. However, the Mo and Cd concentrations in the drilling fluid are far below the ceiling limits for another land-applied material, biosolids (sewage sludge), established by the USEPA and the Colorado Department of Public Health and the Environment (1996). These limits should not be used as a direct comparison, but as a point of reference because biosolids regulations are based on acceptable agronomic rates, and these have not been established for drilling fluid.

We measured potential soil compaction within three days following application at each site. We measured soil penetration resistance with a manual, DICKEY-john (Auburn, IL) soil cone penetrometer. Readings were taken every 7.6 cm of soil depth to 50 cm inside and outside the tire tracks at six locations in each plot. Soil-cone-penetrometer standards (Ameri-

Table 3. Comparison of selected elements in drilling fluids and reported common soil values and USEPA sewage biosolids ceiling limits.

Element	Drilling-fluid range AB-DTPA	Drilling-fluid range Total	Common range for soils†	USEPA biosolids ceiling limits‡
	g kg^{-1}			
Ca	ND§	25–41	0.7–50	none
Na	2.4–46	9.9–20	0.7–7.5	none
Mg	0.2–2.4	3.3–14	0.6–6.0	none
K	0.3–1.2	12–18	0.4–30	none
	mg kg^{-1}			
As	0.05–1.4	7.1–9.3	1.0–30	75
Cd	BDL¶–1.7	1.1–4.7	0.4–0.6	85
Cr	BDL–2.5	36–74	10–200	3000
Cu	3.0–320	23–48	5.0–50	4300
Pb	2.2–112	10–47	10–70	840
Hg	BDL–0.05	BDL–0.1	0.02–1.5	57
Mo	0.31–30	0.2–9.3	0.2–5.0	75
Ni	0.53–36.3	20–28	3.0–100	420
Se	BDL–1.2	0.4–2.5	0.1–4.0	100
Zn	1.7–119	80–124	20–120	7500

† Lindsay (1979) and Kabata-Pendias and Pendias (1989).
‡ Colorado Department of Public Health and the Environment (1996)
§ Not determined.
¶ Below detection limit.

can Society of Agricultural Engineers, 1992) regarding penetration speed and recording were followed. We measured the area impacted by truck wheel traffic to correlate with the area of drilling-fluid coverage.

After planting at both second year sites (A2 and B2), we also measured soil penetration resistance to determine whether differences persisted between the areas that were and were not impacted by truck tires during application. We took readings inside and outside randomly selected tire tracks at five locations approximately 60 cm apart at the end of plots. We measured 10 plots at Site B and 15 plots at Site A. Soil cores were taken to measure soil gravimetric water content before compaction measurements for all second year sites (Ayers and Perumpral, 1982).

Both Year 1 study sites (A1 and B1) were randomized complete block designs with split-plot arrangements composed of four blocks (replications) of 30.5- × 6-m plots. Application method was the main plot and drilling-fluid rate was the sub-plot. The split-plot design was primarily used to reduce anticipated truck travel and compaction around the test site, a concern of the cooperating farmers. After learning how to better handle application logistics and reduce excessive truck traffic, we changed the experimental design at both second year sites (A2 and B2) to a randomized complete block with four replications of each application method and rate. The plot size was reduced to 24.4 × 6 m. We included two new treatments for the Year 2 plots. Without applying drilling fluid, trucks were driven across plots one and two times to represent the new and normal application methods, respectively.

The cooperating farmers planted Sites A1 and B1. Site A1 received 50.4 kg ha^{-1} of seed, and Site B1 received 56 kg ha^{-1} of seed. The Colorado State University Crops Testing Service (CSUCTS) planted Site A2 with approximately 40 kg seed ha^{-1}. The Site B2 producer planted the study plots with the remainder of his field with the same variety at approximately 50.4 kg seed ha^{-1}. All sites were planted with the winter wheat variety TAM 107 using 30.5-cm row widths.

The CSUCTS harvested a 2.1-m swath across the entire plot length at all sites with a plot testing combine that was equipped with a Harvest Master (Logan, UT) yield monitor. The monitor measured and recorded each plot's grain weight, moisture, and test weight. A grain sample for each plot was collected before deposition in the combine hopper. When harvesting the new methods treatment plots, the CSUCTS cut seven rows starting at two rows from the center of the plot. The center seven rows were harvested in the normal application treatment plots. Using this pattern, they harvested the area impacted by two tire tracks during application in normal method plots and one track tire in new methods plots. This pattern allowed us to harvest approximately the same ratio of swath width to tire track impacted soil as when the drilling fluid was applied.

Immediately following harvest, we collected litter samples from straw and chaff deposited by the plot harvesting combine from the center of each plot, oven-dried them at 60°C overnight, and ground them to pass through a 40-mesh sieve. The straw and grain samples were digested with concentrated HNO_3 (Havlin and Soltanpour, 1980) and analyzed for P, K, Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb, Mo, Ba, As, Se, and Hg as described above. We analyzed total N in straw and grain samples by automated dry oxidation (Dumas method) using a LECO (St. Joseph, MI) Model 1000 CHN analyzer (Nelson and Sommers, 1996).

Following grain harvest, four to six soil cores were taken from the surface to 15- to 20-cm depth (plow depth varied between site years) in each plot and composited into one sample. After air-drying, a mechanical stainless steel grinder ground the samples to pass through a 2-mm sieve. The soil elements P, K, Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb, Mo, Ba, As, Se, and Hg were extracted with AB-DTPA and analyzed as previously discussed. We analyzed soil pH and EC_e on saturated pastes. Extracts from the saturated pastes were analyzed by ICP–AES for water soluble Ca, Mg, and Na to calculate SAR.

We analyzed penetrometer readings from both sites using analyses of variance (ANOVA) and the Fisher's Protected least significant difference (LSD) mean separation test (Steele and Torrie, 1980, p. 173–176, 195–209). The LSD was only calculated on data where the ANOVA (*F* test) was significant at the 0.05 probability level for position, method, and rate effects. We computed ANOVA between methods only at nearly equivalent rates.

We analyzed the harvest grain yield and soil and plant elemental data from all site years using ANOVA. Because application rates varied with method, complicating ANOVA interpretation, we also used regression analyses (linear and quadratic) to determine rate effects on grain yield and soil and plant chemical data. The *F* test was used to determine significance at the 0.01 and 0.05 probability levels. We conducted analyses using the PROC GLM (General Linear Model) and PROC ANOVA procedures in SAS (SAS Institute, 1990). Severe wind erosion damaged Block 1 at Site B1 and therefore statistics were performed with only three replications of data from this site year.

RESULTS AND DISCUSSION

Soil pH, Salinity, and Sodicity

Site B1 was the only site that realized a soil pH increase with drilling-fluid application (Fig. 1). We display the results of all application methods together because there is not a significant difference between application methods at equivalent rates. Increasing drilling-fluid rate increased soil pH by as much as 1.5 units. The pH increase is expected, given the relatively high drilling-fluid pH (Table 4) and the drilling-fluid additives $Ca(OH)_2 \cdot xH_2O$ (hydrated lime) and Na_2CO_3 (Table 5). Hydrated lime has a 120 to 135% $CaCO_3$ liming equivalency (California Fertilizer Association, 1985) and Na_2CO_3

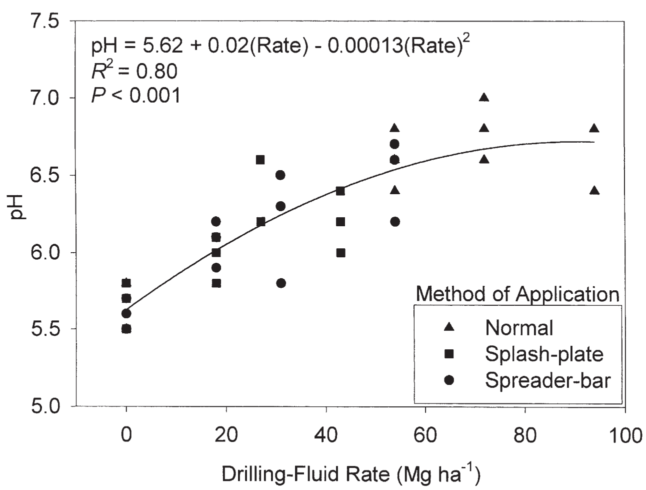

Fig. 1. Effect of drilling-fluid rate on soil pH in the plow layer (top 15–20 cm) immediately following wheat harvest at Site B1 for normal, splash-plate, and spreader-bar methods.

Table 4. Miscellaneous drilling-fluid characteristics from all site years.

	Site year				
	A1				
Parameter†	Pit 1	Pit 2	A2	B1	B2
pH	9.20	9.60	9.80	9.40	8.40
EC_e, ds m^{-1}	1.40	2.40	2.63	1.14	2.47
SAR	ND‡	ND	25.0	ND	23.0
CEC, $cmol_c$ kg^{-1}	12.0	22.0	18.0	14.0	15.0
Organic matter, g kg^{-1}§	11.0	9.00	ND	11.2	ND
Solids, %	33.2	15.8	23.4	29.1	7.23
Sand, %	33.2	8.0	21.0	29.0	32.0
Silt, %	30.0	38.0	37.6	30.0	36.0
Clay, %	34.0	54.0	41.3	41.0	32.0
Total N, mg kg^{-1}	200¶	200¶	ND	300¶	ND
NH_4–N, mg kg^{-1}	3.50	1.90	27.7	5.60	51.7
NO_3–N, mg kg^{-1}	0.200	0.210	19.5	.320	70.5

† EC_e, electrical conductivity saturated-soil paste extract; SAR, sodium adsorption ratio; CEC, cation exchange capacity.
‡ Not determined.
§ Walkley–Black method.
¶ Kjeldahl method.

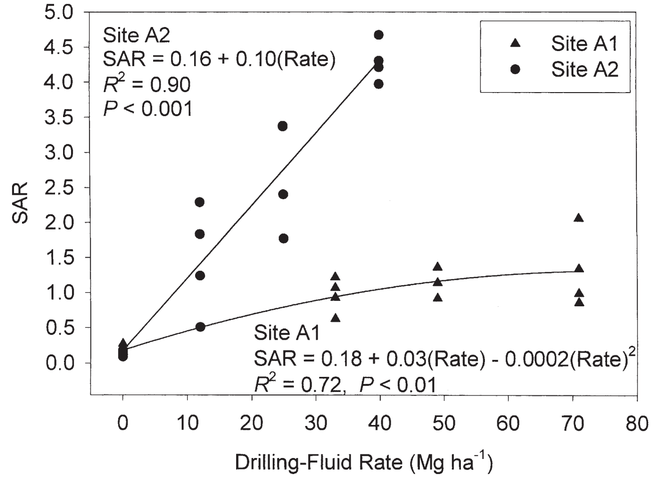

Fig. 2. Effect of drilling-fluid rate on soil SAR in the plow layer (top 15–20 cm) immediately following wheat harvest at Sites A1 and A2 for the normal application method.

is a weak base. Miller and Pesaran (1980) also reported increased pH of sandy acid soils following drilling-fluid application. Site B1 contains a slightly acidic, sandy soil with less buffering capacity than the other site years. These results suggest that 15 to 95 Mg ha^{-1} drilling fluid can raise pH on slightly acidic, sandy soils but not on neutral to basic loamy soils making up the other site years.

Figure 2 shows the effect of increasing drilling-fluid rates on soil SAR at site years A1 and A2. These site years showed the greatest increase in SAR from drilling-fluid application. Although drilling-fluid rates are lower, the SARs in the surface soil for A2 are higher than A1. This observation likely resulted from less leaching of Na and other salts with a later application date and 10 cm less growing season precipitation at A2. We also found statistically significant increases in SAR with drilling-fluid rate at Sites B1 and B2 (Bauder, 1997), but the increase was less than one SAR and poorly explained by linear regression models ($R^2 < 0.50$). Increased SAR is explained by the high AB-DTPA extractable Na (Table 3) and SAR (Table 4) of the drilling fluid applied. The SAR (>15) and pH (>8.5) would categorize the drilling fluid as a sodic soil (United States Salinity Laboratory Staff, 1953). Table 5 shows that some primary drilling-fluid components contain the Na, explaining the high contents found.

Drilling-fluid application significantly increased soil EC_e at three of the four site years (Fig. 3). The drilling fluid applied at these sites had EC_e values that ranged from 1.14 to 2.63 dS m^{-1} (Table 4), compared to EC_e

Table 5. Drilling-fluid additive list supplied by drilling-fluid supplier for all site years.

Component	Approximate amount per well
Water, L	635 000
Na-bentonite, Mg	16.21
Barite ($BaSO_4$), Mg	2.37
Soda ash, Mg	0.55
$Ca(OH)_2{\cdot}xH_2O$, Mg	0.35
Sawdust, Mg	0.29
Drillpac†, Mg	0.22
Lignite, Mg	0.17
PHPA (anionic polymer)‡, L	95

† Unknown or proprietary material.
‡ 30% hydrolyzed polyacrylamide.

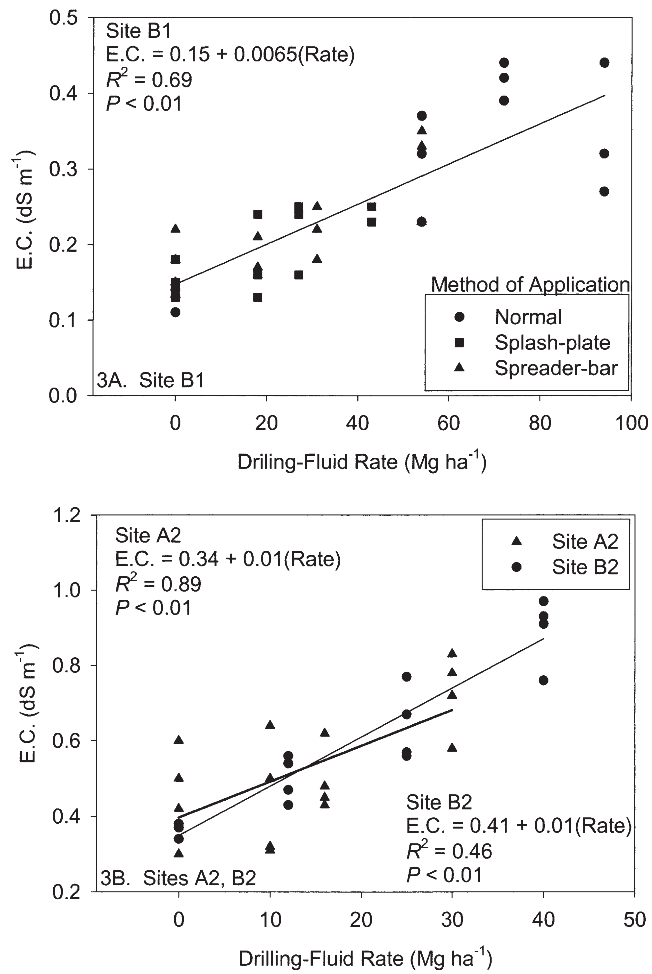

Fig. 3. Effect of drilling-fluid rate on soil electrical conductivity (EC_e) in the plow layer (top 15–20 cm) immediately following wheat harvest at Sites B1, A2, and B2 for all application methods at Site B1 and the normal application method at Sites A2 and B2.

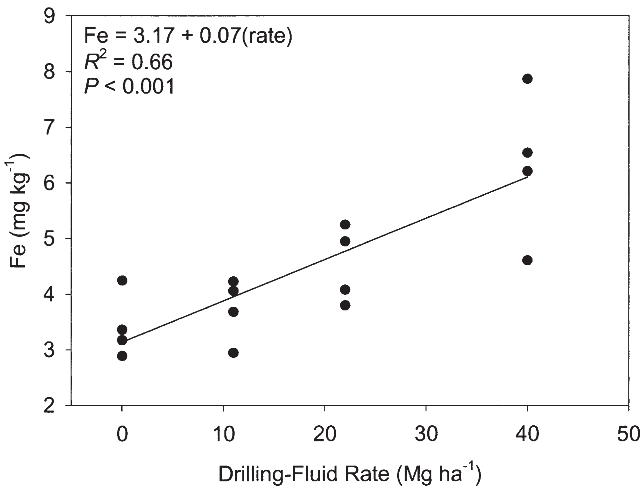

Fig. 4. Effect of drilling-fluid rate on AB-DTPA soil Fe in the plow layer (top 15–20 cm) immediately following wheat harvest at Site A2 for the normal application method.

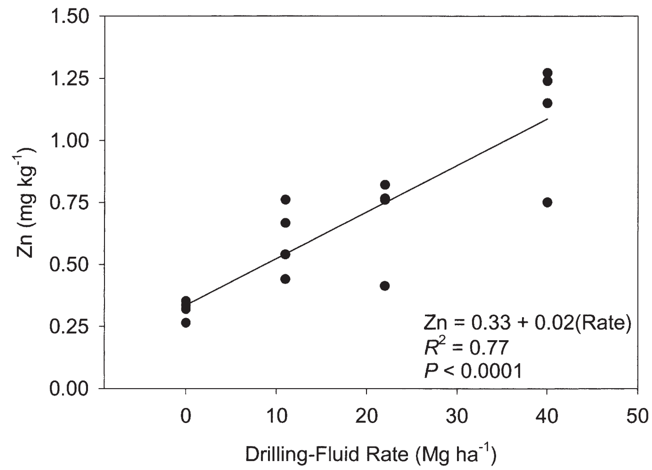

Fig. 5. Effect of drilling-fluid rate on AB-DTPA soil Zn in the plow layer (top 15–20 cm) immediately following wheat harvest at Site A2 for the normal application method.

levels of 0.46 to 0.63 dS m^{-1} in the baseline soil (Table 1), explaining the increase in soil salinity. These results suggest that drilling fluid can increase soil salinity and sodicity as measured by EC_e and SAR. Yet the control EC_e and SAR at all sites were low enough that this comparative rise did not increase the soil Na and total salt status above levels of concern for soil physical properties or production of most agronomic crops (Ayers and Westcot, 1976; United States Salinity Laboratory Staff, 1953). Other workers (Nelson et al., 1984; Miller and Pesaran, 1980) have reported EC_e and exchangeable Na levels high enough to affect plant growth following drilling-fluids application. However, they used rates more representative of spill incidents (up to 500 g drilling-fluid kg^{-1} soil) and drilling fluids with higher initial EC_e than this study. We based application rates on typical industrial applications as practiced by local contractors. Overall, the new methods resulted in lower EC_e and SAR, primarily because of lower rates.

AB-DTPA Extractable Metals

We found increased AB-DTPA extractable Fe in the soil sampled after harvest with the higher application rates of the normal application method at Site A2 (Fig. 4). The drilling fluid applied at this site contained about 550 mg kg^{-1} AB-DTPA extractable Fe compared to an average soil concentration of 3.9 mg kg^{-1} in the control plots, and thus we expect an increase in plant available Fe. Drilling fluid applied at Site A2 had AB-DTPA extractable Zn levels (21.5 mg kg^{-1}) approximately 55 times higher than the control soil (0.38 mg kg^{-1}), and subsequently plant available Zn increased (Fig. 5). Although the detected and predicted increases in plant available Zn and Fe are small, they are important because Zn and Fe are the most frequently reported micronutrients deficiencies in corn, sorghum, and beans in Colorado. Zinc is often deficient on sandy soils similar to Site A1. Other factors contributing to Zn and Fe deficiency include calcareous conditions, high pH, and low organic matter, all conditions frequently encountered in Colorado. However, the highest average Zn values detected are still in the "low to marginal" fertility index. The highest Fe value is in the "high" fertility range (Follett and Westfall, 2001). The benefits of plant available Zn and Fe from drilling fluid to sorghum-sudangrass [*Sorghum bicolor* (L.) *sudanense*] yield were also confirmed in a greenhouse study (Bauder et al., 1999). The results from all four site years indicated that the drilling fluid used in this study did not appreciably change most plant available trace elements.

Drilling-fluid applications generally did not improve the N fertility status of soils under wheat production. Only soil from Site A2 showed a significant change in harvest soil NO_3–N concentration with drilling-fluid rate, increasing by 4 mg kg^{-1} at the 40 Mg kg^{-1} drilling-fluid rate over the control. The fluid applied at this site contained more NO_3–N than all sites but B2 (Table 4), which had lower application rates. Additions of N with the highest drilling-fluid rate were approximately 10 kg ha^{-1} and thus benefits are minimal.

Harvest Straw and Grain

Overall, only small changes were found in harvest straw and grain elemental concentration with drilling-fluid rate and these changes were not consistent across site years or application methods. Elements that did change with drilling-fluid application are presented in Table 6. Straw Mo and P significantly decreased with increasing drilling-fluid rate at Site A1. Small increases in straw Fe, Ba, and grain Zn were also detected at that site year. The Se grain concentration decreased slightly with drilling-fluid application at A2. The general lack of change in harvest straw and grain elemental concentration agrees with the AB-DTPA soil extraction results that drilling fluid applied in our study did not appreciably change the trace metal availability status of an applied soil. The AB-DTPA soil test correlates with micronutrients and trace elements available for plant uptake

Table 6. Selected harvest straw and grain elemental content from two sites.

	Site A1					Site A2
	Straw				Grain	
Drilling-fluid rate†	Mo	P	Fe	Ba	Zn	Se
	mg kg^{-1}					
Control‡	2.2	372	46.4	71.9	22.1	0.50
	Normal application method					
Low	0.98	319	48.0	77.1	24.6	0.28
Medium	0.99	332	61.6	79.6	21.8	0.28
High	0.78	302	52.8	81.7	26	0.24
F test	0.001	0.04	0.04	0.04	0.04	0.03
	Splash-plate application method					
Low	1.10	311	41.0	63.2	24.3	0.39
Medium	0.91	277	50.2	70.1	26.1	0.31
High	0.83	319	55.3	82.3	24	0.22
F test	0.01	0.01	NS§	NS	0.04	0.02
	Spreader-bar application method					
Low	1.27	294	46.5	75.3	23.1	0.59
Medium	1.12	336	43.3	69.6	22.9	0.32
High	0.79	312	54	72.7	25.1	0.25
F test	0.001	NS	NS	NS	0.05	0.01

† Actual drilling-fluid rate provided in Table 2.
‡ Control average of all application methods.
§ Not significant at $P = 0.05$.

(Havlin and Soltanpour, 1981; Soltanpour, 1985; Barbarick and Workman, 1987). These results are comparable with previous work (Nelson et al., 1984) that drilling fluid with no or high purity barite will not increase levels of trace elements in plants grown in the disposal area. No significant changes in straw or grain total N (protein) from all site years were present (data not shown). These results agree with the soil NO_3–N and NH_4–N data that drilling fluid usually does not change the N fertility status of a soil.

Soil Compaction

We measured significantly more penetration resistance ($P < 0.05$) inside the tire tracks than outside the tire tracks following drilling-fluid application. Figure 6A shows a soil profile of penetration resistance inside and outside of the tire tracks at one application site. Soil texture at the site and moisture content at the time of measurement impacted soil strength, but similar profiles were found at other sites and application methods. Surface compaction generally ranged from 2000 to 3000 kPa within tire tracks. This compares to mean penetrometer resistance outside tire tracks of 150 to 400 kPa (Bauder, 1997). Although less severe, we measured significant subsoil compaction following application inside the tire track.

The manufacturer of the soil cone penetrometer classifies soil condition based on penetrometer resistance as good, fair, and poor, for 0 to 1380, 1380 to 2070, and greater than 2070 kPa, respectively. Based on these ratings, truck traffic across the plots reduced the soil condition in the tire track from good (outside the tire track) to poor at the soil surface. Plant root growth can be limited when penetration resistance exceeds 2000 to 4000 kPa (Campbell et al., 1988; Taylor and Gardner, 1963; Ehlers et al., 1983). Thus, immediately following application the soil condition (strength) was generally poor and could be restrictive to root development.

Most drilling fluid is applied during fallow periods in a crop rotation and thus immediate effects on crop growth and development are minimal. Nevertheless, higher soil strength can raise the draft (power) requirement to pull tillage implements. Oskoui and Voorhees (1991) state that soil compaction can affect the amount of energy required for tillage operations, increasing the draft requirement by changing soil strength and by increasing wheel traction. The draft requirement has generally negative effects while traction is positive. An equation developed by Oskoui and Witney (1982) for the prediction of plow draft utilizes cone index (CI) as a primary component, and increases in CI predict higher draft requirement. Higher tillage energy with corresponding CI is also reported by Chamen and Longstaff (1995), Chamen and Cavalli (1994), and Dickson et al. (1989). Although not directly measured in our study, the power requirement to till soils impacted by drilling-fluid application equipment could increase.

Figure 6B provides the results of the compaction measurements at seeding time for Site A2. The higher soil strength measured at 7.5 and 15 cm in the area impacted by truck traffic indicates that some compaction remained 8 weeks following drilling-fluid application. However, the penetration resistance at 7.5 cm decreased by about 1035 kPa from application to planting, largely due to tillage operations for seed-bed preparation and soil wetting and drying.

Grain Yield

Drilling-fluid rate or method of application did not significantly affect grain yield in three of the four site years (Bauder, 1997); therefore, results are only presented for Site B1 (Table 7). The contrast "no drilling-fluid versus drilling-fluid" is significant ($P < 0.05$), providing evidence that the yield of all rates and methods increased over all the control plots. The linear regression of all rates and methods at B1 was also significant but had a low R^2. The linear regression F tests of the splash-plate and normal methods at Site B1 were also significant, but again had low R^2 values. The regressions suggest drilling-fluid rates may increase grain yield on this site, but the increase is small and poorly explained by the models.

The small yield increase at Site B1 is not explained by soil or plant analyses results. Increased soil water availability at planting due to the addition of clay materials and water is a probable explanation. Dry soil conditions and below normal precipitation existed before seeding throughout the 1994–1995 winter. Improved soil water conditions may have aided plant germination, emergence, establishment, and survival. However, above normal precipitation fell in mid-April through harvest, and the crop probably did not undergo significant water stress. Calculated increases for the highest drilling-fluid rate would only increase the clay percentage in the top 20 cm of soil approximately 4 to 5%.

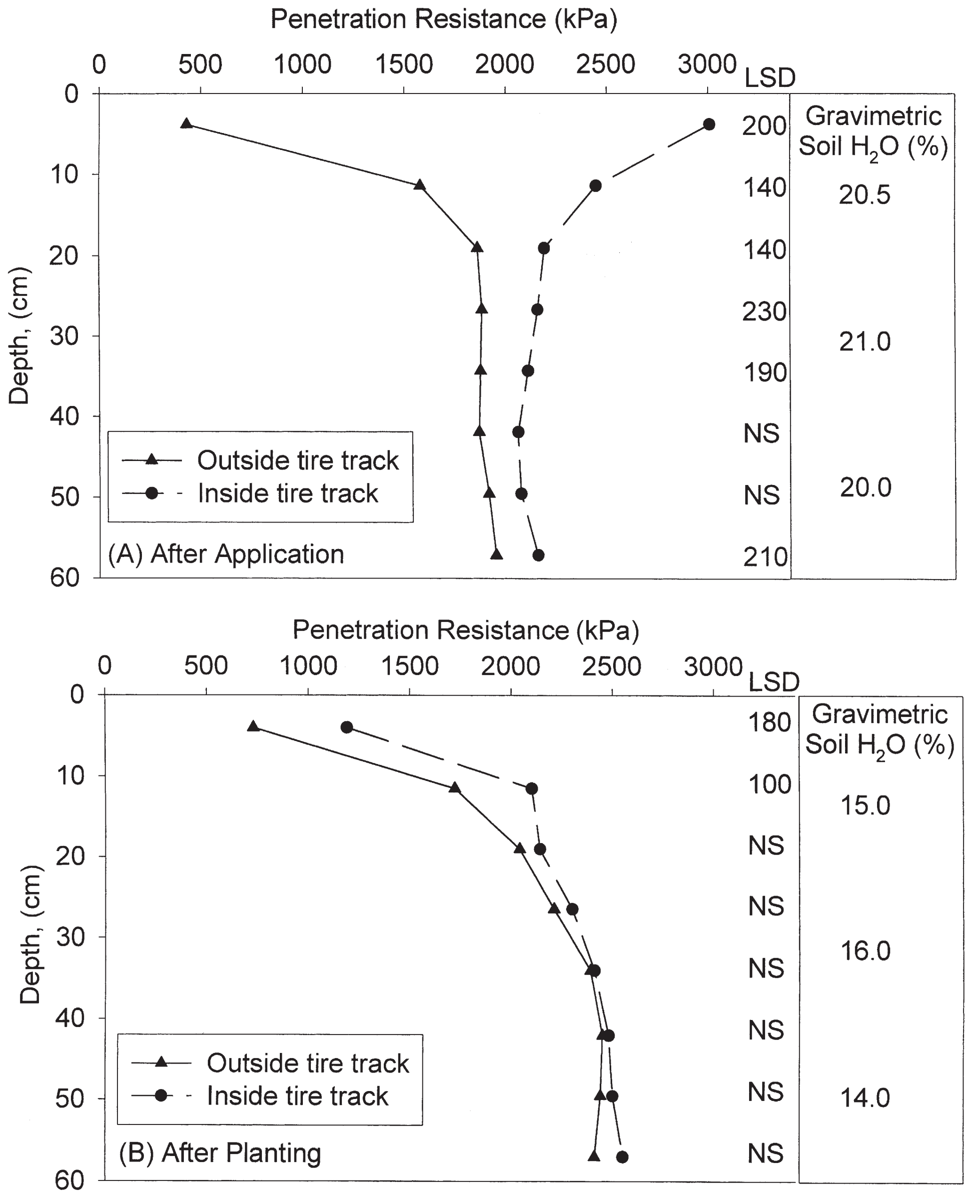

Fig. 6. Examples of penetrometer resistance inside and outside tire track after application (A) and before planting (B) at Site A2.

CONCLUSIONS

Yield results suggest that compaction effects from applying drilling fluid two to five months before planting were not enough to reduce grain yield. Therefore, decreasing truck travel with spreader-bar and splash-plate methods did not result in larger wheat-grain production than the normal method. However, benefits such as better drilling-fluid distribution and possible decreased power requirement in subsequent tillage operations from less areal extent of compaction may result from using the new methods.

Drilling fluid increased soil sodicity and/or salinity at all site years. However, the levels were not detrimental to crop yield at the rates used. Situations where much higher application rates were used resulted in harmful levels are documented in the literature (Miller and Pesaran, 1980; Nelson et al., 1984; McFarland et al., 1992a, 1992b; Younken and Johnson, 1980). Using the new methods, lower rates were obtained that will lessen salt and Na effects.

Extractions representing plant availability and plant analyses results indicate that drilling-fluid application did not significantly increase most trace elements or nutrient concentrations. Small decreases in Se, Mo, and P in straw or grain were detected. Trace elements should not be a limitation to land application with similar drilling fluids and rates.

A single application of drilling fluid at rates up to 94 Mg ha^{-1} caused no statistical improvement or reduction in winter-wheat grain yield at the three of the four site years having loamy to sandy loam soils. The site year with the sandiest soil showed a small yield increase from drilling-fluid application. Our overall conclusion is that

Table 7. Harvest grain yield results from Site B1. Grain yields adjusted to 12% moisture.

Drilling-fluid dry rate	Grain yield	F test	R^2, linear model
Mg ha^{-1}	Mg ha^{-1}		
	Normal application method		
0	3.27		
54	3.57		
72	3.36		
94	3.34		
Average (zero excluded)	3.42	0.02	0.17
	Splash-plate application method		
0	3.12		
17	3.33		
30	3.26		
54	3.45		
Average (zero excluded)	3.33	0.02	0.23
	Spreader-bar application method		
0	3.06		
17	3.07		
27	3.36		
43	3.15		
Average (zero excluded)	3.19	0.71	0.009
Average, all methods and rates	3.31		
Average zero rates	3.13		
	Analysis of variance and contrasts		
Rate†		0.04	0.12
Method‡		0.30	
Method × rate		NA§	
Control vs. fluid¶		0.04	
Normal vs. SP and SB#		0.33	

† Regression of fluid rate across all methods.
‡ At approximately equivalent rates.
§ Not able to be estimated.
¶ All methods, all positive rates vs. all zero rate controls.
# Normal method all rates vs. splash-plate (SP) and spreader-bar (SB) rates (zero rate excluded for contrast).

drilling-fluid application will have no effect on wheat yield for similar soils and management systems when rates are ≤100 Mg ha^{-1}.

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